Influence of Superconductivity on Interlayer Magnetic Exchange Coupling

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PERSONAL SECTION

Some years ago, researchers from the University of Leipzig investigated how position in age hierarchy amongst siblings impacts their personalities and relative intelligence. Although no correlation had been seen between personality and birth order, there was statistical evidence that firstborn siblings tend to show more intelligence than their younger counterparts. When I had first seen that headline as a sophomore in high school with an older sister at a prestigious top university, I remember feeling a sense of relief, and the thought "well that explains it" might have even floated passed my mind. But at the same time, I also felt a bit irritated by this German research study that had absolutely nothing to do with me. Their statistics seemed to validate my subliminal concerns that I would never be able to match my elder sister in intellectual ability or achievement. As though I needed more empirical evidence to prove that I was more average than my sister. I already had plenty of old report cards that said as much.

Ultimately, I have to admit that I am grateful to my sister for being so much better adjusted than I am. The combination of her innate excellence with my incessant need to be the center of attention compelled me to try harder than I ever would have without her around. When I was younger, I never had much of an interest in science or mathematics, until she started to do really well with them. The internal logic must have been something along the lines of "how dare she be good at something. I'll show her by being even better." Nowhere did that apply more readily than the summer before I started high school, when my sister went to attend a research internship program in Boston. At one point that summer my mother dragged me along to visit her and see the lab where she was interning, which really was just a poor excuse for a getaway vacation. The middle school version of me at the time, short and brimming with acne, really had no interest in science research. I entered the Francis Bitter Magnet Laboratory bored and disinterested, due in part to a haughty sense that I had a strong understanding of all there was to know in science. I expected to get in, see some test tubes and colorful liquids, and then leave to maybe visit the aquarium or something.

In the Saturday cartoons of yore, there were occasionally instances where an arrogant and proud character would encounter someone or something completely beyond their skill level, and as a result, would have their dignity utterly crushed. That would be a somewhat appropriate comparison to the experience I had visiting a research lab for the first time. In that lab there were machines worth more than my entire house tenfold. Words and ideas that I had never heard before were thrown around casually, as though I was expected to recognize them. The parts I did understand seemed like science fiction, and I was almost convinced everyone in there was just messing with me. Suddenly my illusion of self-assurance was shattered; I realized how impressive science could really be, and how utterly outclassed I was in terms of scientific knowledge. The worst part of that realization was seeing my sister completely in her element, moving about the lab and testing samples as though she had spent her life there (which, obviously, she had not).

I started high school after that summer with a new mission to stop playing so many online video games and actually give education a whirl (though that did not mean a complete prohibition on the former). I applied myself more in my classes and even did some studying new subject material independently, a hobby that is completely enjoyable and was in no way a terrible, terrible way to spend my weekends. Eventually, I wanted to do what my sister had done, researching advanced physics, to prove to myself that I could do it. I got decent grades and scored well on standardized tests, and eventually, when I was a junior, I applied to the same program that my sister had three years prior, and got accepted.

The summer program that I attended was called RISE (which stands for Research in Science & Engineering) and was run by Boston University. The idea was that rising high school seniors would be matched with research labs around Boston based on their science interests and perform actual research under their mentors. The lab where my sister and I did our research was called the Francis Bitter Magnet Laboratory at MIT, with our research mentor being a brilliant research physicist named Jagadeesh Moodera. It was a bit of a commute to get across the Charles River every day, but I did get some good miles on my health app. In total, I was going to spent six weeks that summer working forty hours a week, doing my best to absorb as much experience and knowledge I could.

The second time I entered through the lab doors, this time minimally taller and with slightly less acne than before, I was prepared to learn and to succeed at research. Alongside four other lab partners, all of whom are now good friends of mine, I was thrust into a world of quantum mechanics and other advanced physics concepts. The first couple weeks were in essence a huge cram session, as we listened to specialized lectures and read enormous books with tiny font size from the lab library (where, coincidently, we set up our main workspace). I had already done my own investigations into condensed matter physics, the principle interest of the lab, after that first time I had visited my sister. In the months leading up to the summer of my own internship, I had also spent embarrassing amounts of time trying to better understand the physics and the math behind it. Although it helped, it was by no means enough, and there is a slight possibility my IQ doubled in that first week alone.

One major aspect to the learning I had to do at the lab was math. Mathematics is insanely important to understanding the complexities of condensed matter physics, something I had not fully realized when studying it on my own. As someone who had not even taken a legitimate calculus class yet, my self-taught understanding of the subject had to be self-taught even more. Although I would never demean the other sciences, physics undoubtedly demands the most advanced mathematics and complex calculations (Also, physics is the best science). Dealing with magnetic coupling constants, calculating energy levels, and just understanding the basic concepts of quantum mechanics, all required me to see math in a new way. Instead of the absurd premises you find on standardized tests, about farmers trying to build pens or whatever, the impact of mathematics was actually tangible before me. Not literally obviously, but you get the idea. Not only that, but to understand data results it was imperative I understand the math behind it as well. Things like hysteresis loops are just pretty pictures if one does not learn how to understand how the parameters are calculated. My research would have been completely impossible had I not been so stereotypically adept at learning more math. Still, math was just one component to the puzzle that my research project ended up being.

In the end, all the knowledge I acquired and all the time I spent making and testing samples made me more perceptive to what science and math could accomplish. With the neverending support of my direct mentor Juan Pedro Cascales Sandoval, I was able to end with an project I could be properly proud of. The research was not so much alive to me; theoretical physics research is essentially the polar opposite of biological life. Instead, I understood things in a new way, as though I had been wearing tinted glasses but had finally ditched them for some good correctives. The experience of being able to research advanced physics in a professional setting is something that I will always cherish, and that I will always be grateful I had the opportunity to do. Even though my interest and been born out of a competitive indignation towards my sister, it has since developed into a real passion I hope to explore more.

My severely subjective piece of advice to anyone trying to pursue a project in mathematics and science would be that there is always more knowledge to be learned. Even after spending my summer in a research lab and learning learning constantly, I feel as though I only barely scratched the surface on that specific field. The more rote information you learn, the easier it becomes to link subjects and make the connections that are essential in doing important work. For instance, even though the lab I was in was explicitly a physics one, I would not have been able to accomplish anything If I had not had a solid base in chemistry. Maybe it's a little frustrating, but the truth is it takes a very long time to become an expert at anything. You should never become complacent with your current level of knowledge. Go read a book or something.

In addition to that, I would also suggest that aspiring scientists and mathematicians get into contact with as many people who can help you as possible. The environment of the research lab was uniquely formative, as I could walk into just about any office and have someone who was able and willing to guide me. Even people who did not specialize in condensed matter physics could understand my research immediately and suggest revisions or give me general advice. One must be humble and recognize when they need other people to help them along; there is a reason hardly any research publications have only one author name on them. I personally despise asking others for help, but nonetheless I swallowed my pride and turned to others when it was the wise thing to do.

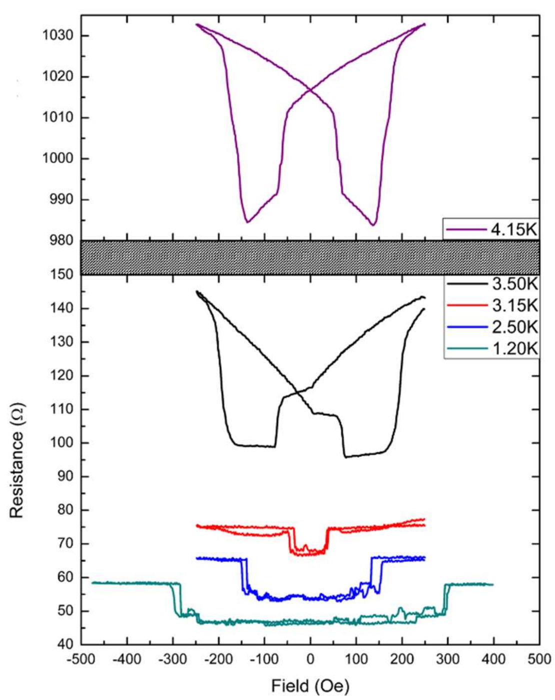
RESEARCH SECTION

The future of science and technology lies in the quantum properties of matter, with fields such as condensed matter physics having already produced innovation like nanotechnology and quantum computation. Superconductivity, the property of some materials to show no electrical resistance at extremely low temperatures, and magnetic exchange coupling, the interaction of ferromagnetic materials over space, have in past research shown tendencies to interact with one another in interesting ways. Should that relationship be better understood, it would enable us to utilize them to improve practical applications of technologies such as maglev trains. Our project investigated these dual phenomena, asking how the two are related, so that we might gain a better understanding to how and why they interact, possibly yielding insight to future applications of their relationship.

As opposed to classical mechanics, quantum mechanics can only be observed on the atomic scale. To accomplish this, we produced trilayer structures of two ferromagnetic insulating layers surrounding a superconducting layer, with the thicknesses being within the scale of nanometers. To do so required extremely tedious work, and the use of advanced thin film sputtering techniques; with limited access to the sputtering chamber we could only make so many, so we made sure to design samples that were more likely to produce usable results. With our fabricated trilayer samples, we were able to observe changes in the electrical resistance of the spacer as the temperature and applied magnetic field varied. Since superconducting phenomenon can only be observed at extremely low temperatures, testing our results required we use a cryostat to lower the temperature of the samples to close to absolute zero (usually less than 10

Kelvin). By continuously observing the samples in this way at a range of temperatures and with changing magnetic field, we were able to correlate the data to specific phenomena that proved the interlayer magnetic exchange coupling between the two outer layers was impacted by the superconductivity of the spacer layer.

Our research showed us that interlayer magnetic exchange coupling is influenced by a superconducting spacer, with the coupling strength between the ferromagnetic layers increasing as the temperature continues to decrease after superconductivity. The likely cause for this correlation is the energy gap that forms when superconductivity emerges creating a connection between the phenomena. This understanding may have broad implications for both theoretical and practical application of condensed matter physics. The connection between them may allow for the development of new quantum spintronics and active magnetic state switching.



An graphical representation of how the resistance in the superconducting sample according to magnetic field behavior in a sample of GdN/NbN/GdN changes as the temperature is varied.

$$J = \frac{\mu_0 \cdot M_S \cdot \Delta H_C \cdot d}{2}$$

The equation that we used to calculate magnetic coupling constant, based on numerous factors including vacuum permeability (μ_0), magnetization saturation (M_S), coercive field differences (ΔH_C), and sample thickness (d).